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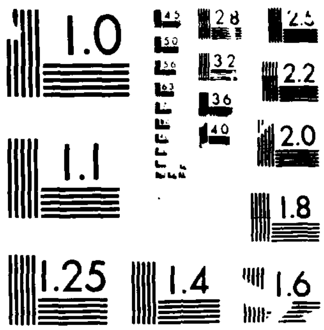

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Marginal Stability of Ion-Acoustic Waves in a Weakly Collisional Two-Temperature Plasma Without a Current

BAMANDAS BASU
JOHN R. JASPERSE

6 August 1987

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The linearized Balescu-Lenard-Poisson equations are solved in the weakly collisional limit to show that ion-acoustic waves in a current-free plasma, which are Landau-damped in the absence of collisions, can become marginally stable due to the undamping effect of electron-ion (e-i) collisions. For $(T_{e0}/T_{i0})^{1/2} << (5/16)(2m_i/m_e)^{1/2}$, the e-i collisional undamping effect dominates the i-i, e-e, and i-e collisional effects, and marginal stability occurs when the collisional undamping rate balances the electron and ion Landau damping rates.

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Preface

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Contents

1. INTRODUCTION 1

2. CLOSED-FORM SOLUTION FOR THE COLLISIONAL DIELECTRIC FUNCTION 3

3. STABILITY ANALYSIS 5

4. CONCLUSION 8

REFERENCES 11

Illustrations

1. Values of Im ω/Re ω From a Numerical Solution of the Dispersion Relation for Ion-Acoustic Waves in a Weakly Collisional Argon Plasma Using Eq. (2) 5

2. Values of the Plasma Parameter (Denoted by g_c) for the Marginal Stability of Ion-Acoustic Waves Using Eq. (2) 6

Marginal Stability of Ion-Acoustic Waves in a Weakly Collisional Two-Temperature Plasma Without a Current

1. INTRODUCTION

For collisionless current-free and current-carrying two-temperature plasmas, the stability of ion-acoustic waves has been studied, and the results have been accepted for many years. For example, linear Vlasov theory predicts that ion-acoustic waves in current-free plasma are Landau-damped, and the plasma is stable.[1] In the presence of a current, ion-acoustic waves become unstable when the current exceeds a threshold value.[1]

For collisional plasmas, the stability situation is unclear. On the one hand, there are studies of collisional, current-free plasma that indicate that ion-acoustic waves are damped.[2,3,4] In their work, Kulsrud and Shen[2] and Ono and Kulsrud[3] assumed that the electrons were isothermal and solved the Fokker-Planck equation for the ions to find that i-i collisions damped ion-acoustic waves. Buti[4] solved the

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1. Fried, B.D., and Gould, R.W. (1961) Longitudinal ion oscillations in a hot plasma, Phys. Fluids, 4:139-147.
2. Kulsrud, R.M., and Shen, C.S. (1966) Effect of weak collisions on ion waves, Phys. Fluids, 9:177-186.
3. Ono, M., and Kulsrud, R.M. (1975) Frequency and damping of ion acoustic waves, Phys. Fluids, 18:1287-1293.
4. Buti, B. (1968) Ion acoustic waves in a collisional plasma, Phys. Rev. 165:195-201.

Fokker-Planck equation in the weakly collisional limit for both the electrons and the ions to find that e-i collisional undamping was small compared with i-i collisional damping for a wide range of wavenumbers and temperatures. On the other hand, there are studies of weakly collisional plasma, driven unstable by the presence of a current, which indicate that e-i collisions have a significant undamping effect[2,5] on ion-acoustic waves and lower the critical current required to produce a current-driven instability. In these studies,[2,5] however, the authors gave no discussion of the stability of the plasma in the limit of zero current. In our view, the stability of ion-acoustic waves in a weakly collisional, current-free plasma is unresolved. The purpose of this report is to present a resolution based upon the Balescu-Lenard-Poisson equations.

The Balescu-Lenard kinetic equations for the one-particle distribution functions for a weakly coupled ($g << 1$) plasma, which may be used to study long wavelength phenomena, are derived by truncating the Bogoliubov-Born-Green-Kirkwood-Yvon hierarchy to the first order in g, by applying the adiabatic approximation and by using time-asymptotic solutions for the pair correlation functions.[6] Here, g is the plasma parameter. Use of the adiabatic approximation implies that the pair correlation functions relax on a time scale that is fast compared with that of the one-particle distribution functions, and use of time-asymptotic solutions for the pair correlation functions implies that plasma waves are not growing in time. Although the adiabatic approximation is known to break down for ω greater than the electron plasma frequency (Jasperse and Basu,[7] Section IVC), we assume that it is valid for low frequencies and long wavelengths. We also assume that the time-asymptotic solutions for the pair correlation functions are valid in stable plasmas up to the limit of marginal stability.

In this report, we present two important results for a weakly collisional, current-free, two-temperature electron-ion plasma: (1) that e-i collisions have an undamping effect on ion-acoustic waves, and (2) that, for appropriate values of the plasma parameters, ion-acoustic waves become marginally stable. Our results are based on the closed-form solution for the dielectric function for the linearized Balescu-Lenard-Poisson kinetic equations, which is given by Eq. (2). The weakly collisional ordering we consider, which is necessary to obtain an iterative

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5. Ong, R.S.B., and Yu, M.Y. (1969) The effect of weak collisions on ion-acoustic wave instabilities in a current-carrying plasma, J. Plasma Phys. 3:425-433; Stefant, R.J. (1971) Influence of electron-ion collisions on ion acoustic waves, Phys. Fluids, 14:2245-2246.

6. Montgomery, D.C., and Tidman, D.A. (1964) Plasma Kinetic Theory, McGraw-Hill, New York.

7. Jasperse, J.R., and Basu, B. (1986) The dielectric function for the Balescu-Lenard-Poisson kinetic equations, Phys. Fluids, 29:110-121.

solution for the collisional dielectric function, imposes two independent restrictions on the parameters that characterize the plasma. They are: (1) $\nu_{ei}/\omega_{ia} \cong (\nu_{ei}/\omega_{pi})(k_e/k) < 1$ or $1/k\lambda_{ei} = \nu_{ei}/kv_{Te} < (m_e/m_i)^{1/2}$; and (2) $\nu_{ii}/\omega_{ia} << 1$ or $1/k\lambda_{ii} = \nu_{ii}/kv_{Ti} < 1$. Here, $\nu_{ei}(\nu_{ii})$ is the e-i (i-i) collision frequency; ω_{ia} is the ion-acoustic wave frequency; ω_{pi} is the ion plasma frequency; k_e is the electron Debye wavenumber; $\lambda_{ei}(\lambda_{ii})$ is the e-i (i-i) mean free path; $v_{Te}(v_{Ti})$ is the electron (ion) thermal speed; and the other quantities have their usual meanings. The approximate marginal stability condition is

$$\nu_{ei}/\omega_{ia} \simeq (\nu_{ei}/\omega_{pi})(k_e/k) = (2\pi)^{1/2}\,[(m_e/m_i)^{1/2} + (T_{e0}/T_{i0})^{3/2}\exp(-3/2 - T_{e0}/2T_{i0})], \tag{1}$$

provided that T_{i0}/T_{e0} and $k/k_e <<1$ and the inequality $1 > \nu_{ei}/\omega_{ia}$ holds. Here, $\nu_{ei} \simeq (2^{1/2} \ln \Lambda_{ei}/12\pi^{3/2})\, g\, \omega_{pe}$, where g is the plasma parameter, $\ln \Lambda_{ei}$ is the Coulomb logarithm, and ω_{pe} is the electron plasma frequency.

2. CLOSED-FORM SOLUTION FOR THE COLLISIONAL DIELECTRIC FUNCTION

We begin with the nonlinear Balescu-Lenard-Poisson kinetic equations[6] for an unmagnetized, two-temperature electron-ion plasma. We consider a quasi-steady, zero-order state where the zero-order distribution functions are Maxwellian with unequal temperatures ($T_{e0} \neq T_{i0}$). In order to obtain the dielectric function that contains the effects of e-e, e-i, i-e, and i-i collisions to the first order, we linearize the equations for small amplitude, electrostatic perturbations about the zero-order state and apply the collisional propagator expansion method[8] appropriately generalized for a two-constituent plasma. Using the techniques discussed in Jasperse and Basu,[7] we find that all of the integrals that appear in the dielectric function may be reduced to the simpler forms presented here. Since the algebra involved is straightforward but lengthy, the details of the calculation will be reported elsewhere. The dielectric function to the first order in collisionality is:

$$\epsilon^{(1)}(\underset{\sim}{k}, \omega) = 1 + \sum_{\alpha} (k_\alpha/k)^2 \{W_0(z_\alpha) + i \sum_{\beta} \eta_{\alpha\beta}\, [A_{\alpha\beta}(z_\alpha) + B_{\alpha\beta}(z_\alpha)]\}. \tag{2}$$

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8. Jasperse, J. R. (1984) A propagator expansion method for solving linearized plasma kinetic equations with collisions, Phys. Letters, 106A:379-382.

Here, $k_\alpha^2 = 4\pi\, n_0 q_\alpha^2 / T_{\alpha 0}$, $k = |\underset{\sim}{k}|$, $z_\alpha = \omega / k v_{T\alpha}$, $v_{T\alpha}^2 = T_{\alpha 0}/m_\alpha$, $\eta_{\alpha\beta} = \nu_{\alpha\beta} / k v_{T\alpha}$, $\nu_{\alpha\beta} = (4/3)(2\pi)^{1/2} (q_\alpha^2 q_\beta^2 n_o / m_\alpha^{1/2} T_{\alpha 0}^{3/2})(1 + m_{\alpha\beta})(1 + \varepsilon_{\alpha\beta})^{-3/2}$.

$\ln \Lambda_{\alpha\beta}$ is the $\alpha - \beta$ collision frequency, $\varepsilon_{\alpha\beta} = v_{T\beta}^2 / v_{T\alpha}^2$, $m_{\alpha\beta} = m_\alpha / m_\beta$, and

$$A_{\alpha\beta}(\zeta) = (\tfrac{1}{2})(1 + \varepsilon_{\alpha\beta})^3 (1 + m_{\alpha\beta})^{-1} \{[1 + 3\varepsilon_{\alpha\beta}(T_{\alpha\beta} - 1)(1 + \varepsilon_{\alpha\beta})^{-1}]$$

$$\times I_{\alpha\beta}^{(0)}(\zeta) + 6\, m_{\alpha\beta}\, q_{\beta\alpha} (1 + \varepsilon_{\alpha\beta})^{-1}$$

$$\times [(1 + m_{\alpha\beta}) J_{\alpha\beta}^{(0)}(\zeta) + i(T_{\alpha\beta} - 1) J_{\alpha\beta}^{(1)}(\zeta)]\},$$

$$B_{\alpha\beta}(\zeta) = 3\varepsilon_{\alpha\beta}(T_{\alpha\beta} - 1)(1 + q_{\beta\alpha} T_{\alpha\beta})(1 + \varepsilon_{\alpha\beta})^{3/2}(1 + m_{\alpha\beta})^{-1} I_{\alpha\beta}^{(1)}(\zeta),$$

$$I_{\alpha\beta}^{(n)}(\zeta) = -\zeta^{1-n} \int_0^1 d\mu\, \mu^2 (1 - \mu^2 + \varepsilon_{\alpha\beta})^{-(4-n)/2} W_{2-n}[a_{\alpha\beta}(\mu)\zeta],$$

$$J_{\alpha\beta}^{(n)}(\zeta) = -\zeta \int_0^1 d\mu\, \mu^2 (1 - \mu^2 + \varepsilon_{\alpha\beta})^{-n} \int_0^\infty dt\, t^{1-n}$$

$$\times \exp[i b_{\alpha\beta}(\mu)\zeta t - c_{\alpha\beta}(\mu) t^2]\, W_n[a_{\alpha\beta}(\mu)\zeta + i\varepsilon_{\alpha\beta}\mu^2 t].$$

In the above $n = 0, 1$, $T_{\alpha\beta} = T_{\alpha 0}/T_{\beta 0}$, $a_{\alpha\beta} = [(1 + \varepsilon_{\alpha\beta})/(1 - \mu^2 + \varepsilon_{\alpha\beta})]^{1/2}$, $q_{\beta\alpha} = q_\beta / q_\alpha$, $b_{\alpha\beta} = [(1 + \varepsilon_{\alpha\beta})(1 - \mu^2 + \varepsilon_{\alpha\beta})]^{1/2}$, and $c_{\alpha\beta} = (\tfrac{1}{2})\varepsilon_{\alpha\beta} \times [(1 - \mu^2)(1 + \varepsilon_{\alpha\beta})^2 + \varepsilon_{\alpha\beta}\mu^4]$. The W_n-functions are given by

$$W_n(\zeta) = i^n \int_0^\infty dt\, t^{n-1} \exp(i\zeta t - t^2/2),$$

where $n = 0, 1, 2, \ldots$, $W_n(\zeta) = (d/d\zeta)^n W_0(\zeta)$, and $W_0(\zeta)$ is related to the plasma dispersion function $Z(\zeta)$ by $W_0(\zeta) = 1 + (\zeta/2^{1/2}) Z(\zeta/2^{1/2})$. In Eq. (2), $\underset{\sim}{k}$ has been oriented along the positive z-axis. We note that, when $T_{e0} = T_{i0}$ in Eq. (2), we obtain Eqs. (1) and (2) of Jasperse and Basu.[9] Also, when $T_{e0} = T_{i0}$ and ion motion is neglected, we obtain Eqs. (26) through (30) of Jasperse and Basu[7] for the high-frequency dielectric function.

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9. Jasperse, J.R., and Basu, B. (1987) Collisional enhancement of low-frequency density fluctuations in a weakly collisional electron-ion plasma, Phys. Rev. Letters, 58:1423-1425.

3. STABILITY ANALYSIS

Numerical solutions of the dispersion relation, $\varepsilon^{(1)}(\underset{\sim}{k}, \omega) = 0$, for ion-acoustic waves, that is, for $v_{Ti} < |\omega/k| < v_{Te}$ and $k/k_e < 1$, and for $\Lambda_{\alpha\beta} = 12\pi/g$, are presented in Figures 1 and 2. Figure 1 shows the dependence of $\mathrm{Im}\,\omega/\mathrm{Re}\,\omega$ ($\mathrm{Im}\,\omega < 0$ means stability) on k/k_e and T_{e0}/T_{i0} for an Argon plasma with $g = 2 \times 10^{-5}$.

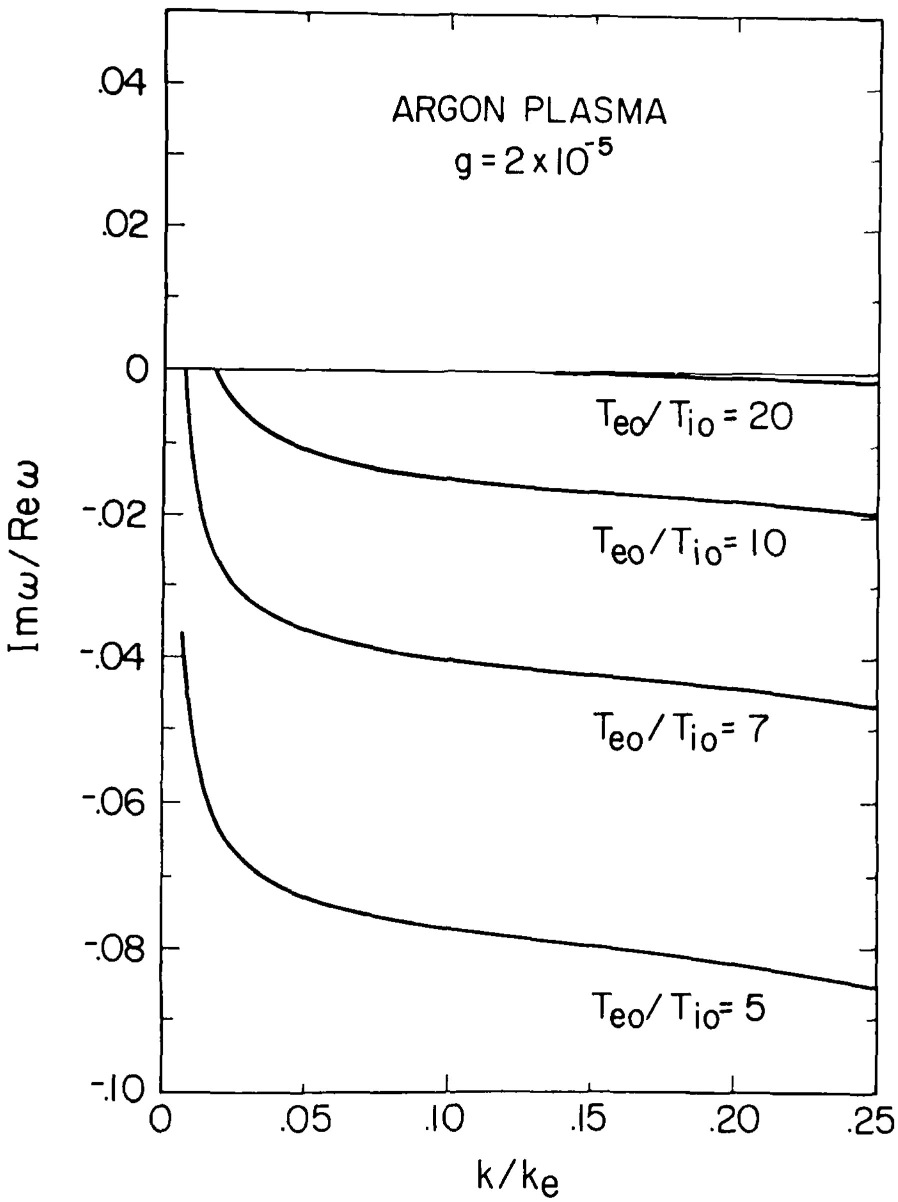

Figure 1. Values of $\mathrm{Im}\,\omega/\mathrm{Re}\,\omega$ From a Numerical Solution of the Dispersion Relation for Ion-Acoustic Waves in a Weakly Collisional Argon Plasma Using Eq. (2)

Figure 2, where we have plotted the values of g (denoted by g_c) for marginal stability as a function of m_e/m_i and T_{e0}/T_{i0} for $k/k_e = 0.1$, shows that marginal stability results for a smaller amount of collisionality in heavier-ion plasmas having larger values of T_{e0}/T_{i0}. We also find from the numerical results that, when T_{i0} is increased by a sufficient amount relative to T_{e0}, a value of T_{e0}/T_{i0} is reached where ion Landau damping overcomes e-i collisional undamping and stabilizes the plasma for all values of m_e/m_i, k/k_e, and g.

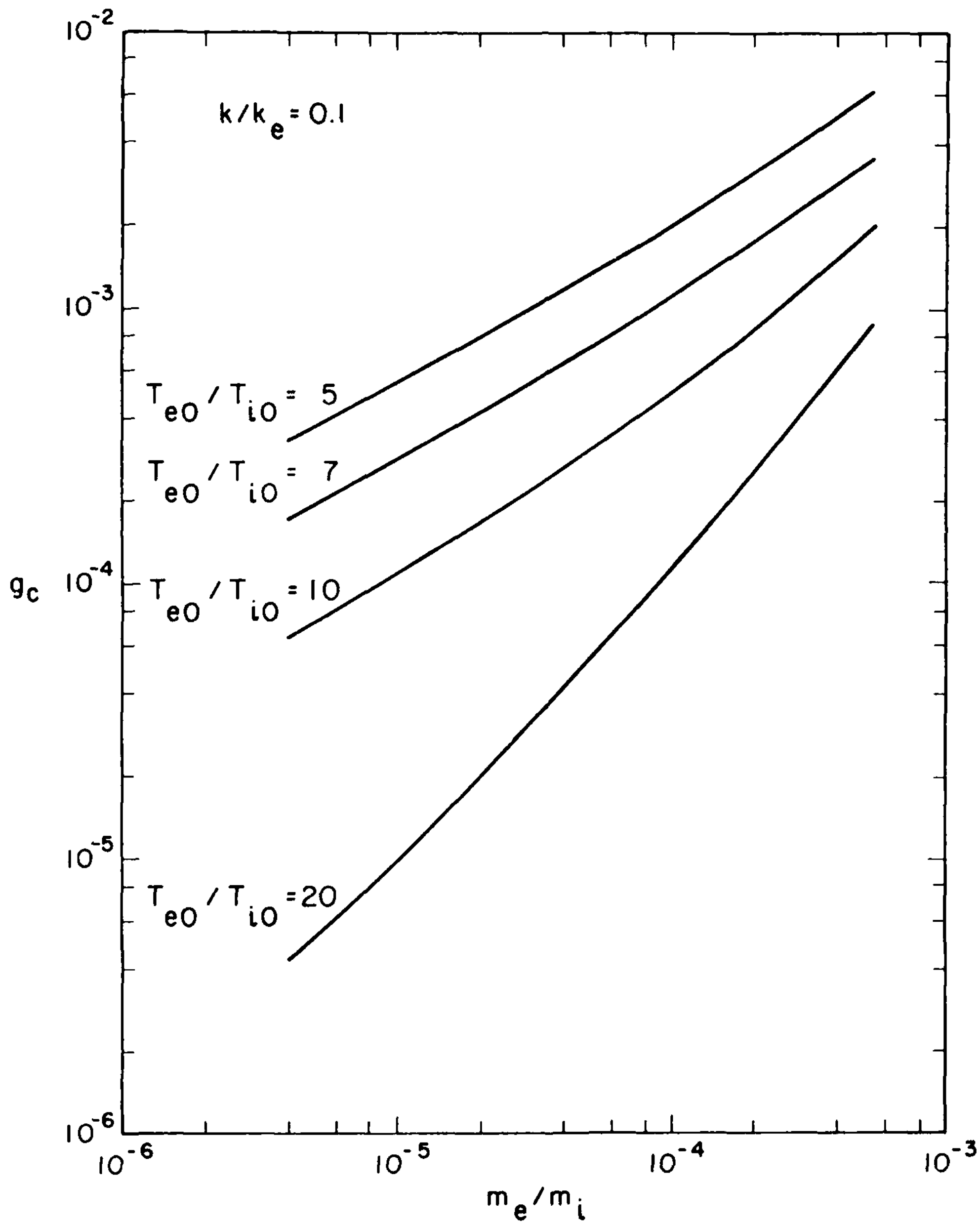

Figure 2. Values of the Plasma Parameter (Denoted by g_c) for the Marginal Stability of Ion-Acoustic Waves Using Eq. (2)

In what follows, we present some analytical results that we obtain from Eq. (2) by making appropriate approximations. From Eq. (2), we see that $\varepsilon^{(1)}$ contains eight collisional terms, two terms for each of the four collisional pairs: e-e, e-i, i-e, i-i. The imaginary parts of the terms for each of the four collisional pairs, denoted by $\chi_{\alpha\beta}^{(i)}$, contribute to the imaginary part of the wave frequency as damping or undamping. For ion-acoustic waves at long wavelengths, we find that $\chi_{ei}^{(i)} : \chi_{ii}^{(i)} : \chi_{ee}^{(i)} : \chi_{ie}^{(i)} \cong 1 : (16/5)(m_e/2m_i)^{1/2}(T_{e0}/T_{i0})^{1/2} : m_e/m_i : m_e/m_i$. We also find that $(m_e/m_i)\,|J_{ei}^{(0)}|$, $(m_e/m_i)\,|J_{ei}^{(1)}|$ and $\varepsilon_{ei}\,|I_{ei}^{(1)}| << I_{ei}^{(0)}$. Hence, for $m_e/m_i << 1$ and $(T_{e0}/T_{i0})^{1/2} << (5/16)(2m_i/m_e)^{1/2}$, $\varepsilon^{(1)}$ may be well approximated by

$$\varepsilon^{(1)}(\underset{\sim}{k}, \omega) \cong 1 + \sum_{\alpha} (k_\alpha/k)^2\, W_0(z_\alpha) + (i/2)(k_e/k)^2\, \eta_{ei}\, I_{ei}^{(0)}(z_e).$$

In addition, we find that for $v_{Ti} << |\omega/k| << v_{Te}$, $I_{ei}^{(0)} \sim -1/z_e$, and that $\varepsilon^{(1)}$ may be approximated asymptotically by using the appropriate expansions for W_0:

$$\begin{aligned}\varepsilon^{(1)}(\underset{\sim}{k}, \omega) \sim\ & 1 + (k_e/k)^2 - (\omega_{pi}/\omega)^2 (1 + 3z_i^{-2}) + i(k_e/k)^2 \\ & \times\{(\pi/2)^{1/2}(m_i/m_e)^{1/2} z_e\, [(m_e/m_i)^{1/2} \\ & + (T_{e0}/T_{i0})^{3/2} \exp(-z_i^2/2)] - (\nu_{ei}/2\omega)\}. \qquad (3)\end{aligned}$$

Ion-ion collisions result in a damping term in the dielectric function that may be approximated analytically by $(8i/5)(T_{e0}/T_{i0})(\nu_{ii}/\omega)(k_e/k)^2 z_i^{-4}$ and can be neglected compared to the e-i undamping term for $(T_{e0}/T_{i0})^{1/2} << (5/16)(2m_i/m_e)^{1/2}$. Solving the dispersion relation for $k/k_e << 1$ and $|\mathrm{Im}\,\omega| << \mathrm{Re}\,\omega$ using Eq. (3), we obtain

$$\mathrm{Re}\,\omega \simeq k\,[(T_{e0} + 3\,T_{i0})/m_i]^{1/2} \equiv \omega_{ia}, \qquad (4)$$

$$\begin{aligned}\mathrm{Im}\,\omega \simeq -\omega_{ia}\, \{ & (\pi/8)^{1/2} [(m_e/m_i)^{1/2} \\ & + (T_{e0}/T_{i0})^{3/2} \exp(-3/2 - T_{e0}/2T_{i0})] - (\nu_{ei}/4\omega_{ia})\}, \qquad (5)\end{aligned}$$

which are valid when $T_{i0} << T_{e0}$ and $\nu_{ei} < \omega_{ia}$. In Eq. (4), we have neglected the first-order collisional shift in the expression for $\mathrm{Re}\,\omega$. Eq. (5) for $\mathrm{Im}\,\omega$ is the sum of three terms: The first is electron Landau damping, the second is ion Landau damping, and the third is an undamping term due to e-i collisions. From Eq. (5), we find the marginal stability condition given in Eq. (1). When $T_{e0}/T_{i0} \gtrsim 20$ and $k/k_e \lesssim 0.1$, Eq. (5) yields values that are within 10 percent of the results shown in Figures 1 and 2. For smaller values of T_{e0}/T_{i0}, numerical solutions are necessary for accurate results.

By taking the velocity moments of the perturbed electron distribution function and neglecting collisionless damping effects, we find that

$$\tilde{n}_{e1}/n_0 \cong [1 - (i/2)(\nu_{ei}/\omega)] (e\tilde{\varphi}_1/T_{e0}), \tag{6}$$

$$\tilde{T}_{e1}/T_{e0} \cong (i/2)(\nu_{ei}/\omega)(e\tilde{\varphi}_1/T_{e0}), \tag{7}$$

where $\tilde{n}_{e1}$, $\tilde{\varphi}_1$, and $\tilde{T}_{e1}$ are, respectively, the perturbed electron density, perturbed potential and perturbed electron temperature in $\underset{\sim}{k}$ - ω space. These results show that the electrons are not isothermal and that there is a collision-induced, temperature perturbation associated with the ion-acoustic mode. We recall that in the linear Vlasov theory of the ion-acoustic mode, the electrons are isothermal and $\tilde{T}_{e1} = 0$.

We have performed a quasilinear analysis of the Balescu-Lenard-Poisson equations. We find that

$$\frac{1}{T_{e0}(t)} \frac{\partial}{\partial t} T_{e0}(t) = -\frac{2}{3} \int d\underset{\sim}{k} \, (\mathrm{Im}\, \omega_{\underset{\sim}{k}}) \, | e\tilde{\varphi}_1(t) / T_{e0}(t) |^2, \tag{8}$$

where $\mathrm{Im}\, \omega_{\underset{\sim}{k}}$ is given by Eq. (5). For stable ion-acoustic waves, Eq. (8) indicates that T_{e0} initially increases with time while the electric field energy density, $k^2 |\tilde{\varphi}_1(t)|^2/8\pi$, initially decreases since $\partial |\tilde{\varphi}_1(t)|^2/\partial t = 2\, \mathrm{Im}\omega_{\underset{\sim}{k}} |\tilde{\varphi}_1(t)|^2 < 0$. A more detailed discussion will be presented elsewhere.

4. CONCLUSION

In conclusion, we have shown by using the Balescu-Lenard-Poisson equations that e-i collisions have an undamping effect on ion-acoustic waves for weakly collisional plasma. The fact that this undamping effect persists even when $T_{e0} = T_{i0}$ is discussed in Jasperse and Basu.[9] For thermal equilibrium ($T_{e0} = T_{i0}$) plasma, the undamping effect of e-i collisions on thermal fluctuations at the ion-acoustic frequency from Jasperse and Basu[9] is $1.2\,(\nu_{ei}/4)$. For nonequilibrium ($T_{e0} >> T_{i0}$) plasma, the undamping effect of e-i collisions from Eq. (5) is $\nu_{ei}/4$. We see that the undamping effect operates for equilibrium as well as nonequilibrium plasma, and has a value which, except for the $T_{e0}^{-3/2}$ dependence of ν_{ei}, is nearly independent of T_{e0} and T_{i0}. The difference between equilibrium and nonequilibrium plasma is that, for equilibrium plasma, ion Landau damping easily overcomes e-i collisional undamping, and the plasma is stable, whereas for nonequilibrium plasma, a wavelength can be found where e-i collisional undamping balances ion and electron Landau damping, and the plasma is marginally stable. Our analysis suggests that when ν_{ei}/ω_{ia} exceeds the quantity on the right-hand side of Eq. (1) a collision-driven ion-acoustic instability occurs. Although the Balescu-Lenard collision operator may not be valid for unstable waves, it is our belief that such an instability exists but the actual threshold condition may be slightly different. In order to test this idea, we suggest that an experiment be performed. The threshold parameters given in Figure 2 should be useful in designing such an experiment.

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9. Jasperse, J.R., and Basu, B. (1987) Collisional enhancement of low-frequency density fluctuations in a weakly collisional electron-ion plasma, Phys. Rev. Letters, 58:1423-1425.

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